$J/\psi$ PRODUCTION IN p-Pb COLLISIONS
WITH ALICE AT THE LHC

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for the ALICE collaboration

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• Motivation
• Analysis
• Results
  ‣ Forward-$\gamma$ to backward-$\gamma$ ratio ($R_{FB}$)\textsuperscript{*}
  ‣ Nuclear modification factor ($R_{pPb}$)\textsuperscript{*}
  ‣ $R_{pPb}$ $p_T$ dependence
  ‣ $Q_{pPb}$ vs ZN event activity \textcolor{red}{New ALICE preliminary}
  ‣ Relative yields vs charged particle multiplicity \textcolor{red}{New ALICE preliminary}
  ‣ Relative $<p_T>$ vs charged particle multiplicity \textcolor{red}{New ALICE preliminary}
• Conclusions

\textsuperscript{*} Forward-$\gamma$ and backward-$\gamma$ results are \textbf{published results} from:

\textit{J/$\psi$ production and nuclear effects in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV}, JHEP 02 (2014) 073
Why study p-Pb collisions?

- Understand **cold nuclear matter** effects
- Necessary to disentangle **hot (QGP related)** and **cold nuclear matter** effects in Pb-Pb collisions

**Cold nuclear matter effects:**

- **Initial state effects:** **Gluon shadowing** [1] (or **saturation** [2])
  - Shadowing: gluon pdf in a nucleus ≠ in a nucleon (saturation: when energy is high enough, gluons start to recombine with each other)
    
    Expected to be significant at LHC energies, depending on the kinematic domain

- **Coherent energy loss** [3]
  - The medium-induced gluon radiation modifies the initial-state gluon kinematics and affects the final-state $c\bar{c}$ pair

- **Final state effects:** **Nuclear absorption** [4]
  - Destruction of pre-resonant or final state $J/\psi$ by collisions with nucleons
    Should be negligible at the LHC since crossing-times are smaller than quarkonium formation times.

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\[ J/\psi \rightarrow e^+e^- \]
-0.9 < \( y_{\text{lab}} \) < 0.9
\( p_T > 0 \) GeV/c

LHC beam asymmetry

- \( 2.03 < y_{\text{cms}} < 3.53 \) (\(-1.37 < y_{\text{cms}} < 0.43\))
- \( 1.8 \cdot 10^{-5} < x_{\text{Bjorken}} < 8.1 \cdot 10^{-5} \) (\(0.4 \cdot 10^{-3} < x_{\text{Bjorken}} < 2.4 \cdot 10^{-3}\))

Hypothesis:

- \( 4.46 < y_{\text{cms}} < -2.96 \)
- \( 1.2 \cdot 10^{-2} < x_{\text{Bjorken}} < 5.3 \cdot 10^{-2} \)

Common range:

\[ \Delta y |_{\text{CMS}} = 0.5 \log \left( \frac{Z_{\text{Pb}}A_p}{Z_pA_{\text{Pb}}} \right) = 0.465 \]
• Event selection
  • Minimum Bias (MB) trigger: Coincidence of the two VZERO (2.8 < \( \eta_{\text{lab}} \) < 5.1 and -3.7 < \( \eta_{\text{lab}} \) < -1.7)
  • Rejection of beam-gas and electromagnetic interactions
  • SPD used for vertex determination and charged particle multiplicity measurement
  • ZDC used for event activity determination (in particular ZN)
  • |\( Z_{\text{vertex}} \)| < 10 cm (for dielectron analysis and for charged particle multiplicity measurement)

• Dimuon trigger
  • MB & two opposite sign muon tracks in the trigger chambers

• Dimuon analysis cuts
  • Muon trigger matching
    • -4 < \( \eta_{\mu_{\text{lab}}} \) < -2.5
    • 17.6 cm < \( R_{\text{abs}} \) < 89.5 cm (\( R_{\text{abs}} \) is the track radial position at the end of the absorber)
    • 2.5 < \( y_{\mu_{\mu_{\text{lab}}} \text{lab}} \) < 4

• Dielectron trigger
  • MB

• Dielectron analysis cuts
  • Track quality cuts
    • -0.9 < \( \eta_{\text{e_{lab}}} \) < 0.9 and \( p_T \) > 1 GeV/c
  • Rejection of tracks from photon conversion
  • TPC electron identification
- **Background**: variable-width Gaussian or polynomial x exponential parametrization.
- **Resonance**: Crystal Ball or pseudo-gaussian function with tails parameters tuned on MC

- **Background**: subtracted using normalized like-sign pair distribution or parametrized using ratio of polynomial functions.
- **Resonance**: bin by bin counting in 2.92-3.16 GeV/c²
### Computed in the $y_{\text{cms}}$ range common to p-Pb and Pb-p (2.96 < $|y_{\text{cms}}|$ < 3.53)

**Independent of nuclear thickness ($T_{pPb}$) and pp cross section**

- Pure shadowing slightly overestimates data
- Shadowing with energy loss in good agreement with data
- Data are consistent with shadowing + energy loss models
- Dependence with $p_T$ is observed
- The suppression is stronger at low $p_T$
\[ R_{pPb} = \frac{Y_{J/\psi}}{\langle T_{pPb} \rangle \sigma_{pp}} \]

- Computed in the **full acceptance windows** (2.03 < \( y_{\text{cms}} \) < 3.53 and -4.46 < \( y_{\text{cms}} \) < -2.96)

- **Nuclear thickness function**
\[ \langle T_{pPb} \rangle = 0.0983 \pm 0.0034 \text{ mb}^{-1} \]

- **pp reference cross-section**: no measurement at required energy, need to interpolate. Two step procedure in both analyses.
  - **Dimuon analysis** \(^1\):
    1) \( \sqrt{s} \) interpolation: performed bin-per-bin in rapidity (or \( p_T \)) using available ALICE pp results at 2.76 and 7 TeV
    2) Further rapidity extrapolation: due to rapidity shift, p-Pb \( y_{\text{cms}} \)-range lies slightly outside the pp \( y_{\text{cms}} \)-range
  - **Dielectron analysis**:
    1) \( \sqrt{s} \) interpolation: performed using available PHENIX, CDF and ALICE results at \( y \approx 0 \)
    2) \( p_T \) dependence: phenomenological scaling inspired by reference \(^2\)

\(^1\) ALICE-PUBLIC-2013-002
\(^2\) arXiv: 1103.2394
- Strong suppression at mid and forward rapidity
- No suppression at backward rapidity

Data are consistent with models including shadowing and/or energy loss

Color Glass Condensate (CGC) inspired model underestimates the data

Systematic uncertainties:
- Colored boxes: uncorrelated
- Shaded areas: partially correlated
- Box around unity: fully correlated
$R_{pPb}$ vs $p_T$

**Backward Rapidity**
- Small $p_T$ dependence, compatible with unity

**Midrapidity**
- Small $p_T$ dependence, compatible with unity for $p_T \gtrsim 3$ GeV/$c$
- Data are consistent with shadowing only model (calculation for $p_T > 2.5$ GeV/$c$)
- Coherent energy loss overestimates suppression at forward rapidity and low $p_T$
- CGC overestimates suppression at forward rapidity

**Forward Rapidity**
- Increases with $p_T$, compatible with unity for $p_T \gtrsim 5$ GeV/$c$

**Events**
- ALICE Preliminary
- $p$-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, inclusive $J/\psi \to \mu^+\mu^-$
- $-4.46 < y_{\text{ cms}} < -2.96$, $L_{\text{ int}} = 5.8$ nb$^{-1}$

**Figure Details**
- EPS09 NLO (Vogt)
- CGC (Fujii et al.)
- ELoss with $q_E = 0.075$ GeV$^2$/fm (Arleo et al.)
- EPS09 NLO + ELoss with $q_E = 0.075$ GeV$^2$/fm (Arleo et al.)

**ALICE Preliminary**
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- $p$-Pb, $\sqrt{s_{NN}} = 5.02$ TeV, inclusive $J/\psi \to e^+e^-$
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- $2.03 < y_{\text{ cms}} < 3.53$, $L_{\text{ int}} = 5.0$ nb$^{-1}$
Assumptions:
- Production mechanism: $g + g \rightarrow J/\psi$
- CNM effects factorize in p-nucleus and are dominated by shadowing

- Increase of $S_{J/\psi}$ at low $p_T$ (observation that favors recombination scenario in Pb-Pb)
- Strong suppression at high $p_T$
$Q_{pPb}$ has the same definition of $R_{pPb}$. A different notation is used due to potential biases in the event activity estimator (ZN energy) not related to nuclear effects.

- **Decrease of $Q_{pPb}$ from low to high event activity at forward rapidity is observed.**
- **$Q_{pPb}$ is consistent with unity at backward rapidity.**

**Systematic uncertainties:**
- Colored boxes: uncorrelated
- Shaded areas: partially correlated
- Box around unity: fully correlated

**Plot Details:**
- Inclusive $J/\psi \rightarrow \mu^+ \mu^-$, p-Pb $\sqrt{s_{NN}} = 5.02$ TeV, $0<p_T<15$ GeV/c
- $2.03<y_{\text{cms}}<3.53$, p-going direction
- $-4.46<y_{\text{cms}}<-2.96$, Pb-going direction

See poster by I. Lakomov
$Q_{pPb}$ vs $p_T$ : EVENT ACTIVITY DEPENDENCE

- **Increase** of $Q_{pPb}$ for increasing event activity at **backward** rapidity. A clear $p_T$ dependence is also observed at high event activity, with a stronger enhancement at high $p_T$.

- **Decrease** of $Q_{pPb}$ for increasing event activity at **forward** rapidity. A clear $p_T$ dependence is also observed at high event activity, with a stronger suppression at low $p_T$.

- For increasing event activity the difference between forward and backward rapidity results becomes much stronger.
• **Strong increase** of relative J/ψ yields at forward and backward rapidity with relative multiplicity
• **Strong increase** of relative $J/\psi$ yields at forward and backward rapidity with relative multiplicity

• At backward rapidity similar behavior as found in pp collisions, deviation at forward rapidity
**Strong increase** of relative $J/\psi$ yields at forward and backward rapidity with relative multiplicity

- At backward rapidity similar behavior as found in pp collisions, deviation at forward rapidity

- D meson relative yield at central rapidity shows also a **strong increase**
The relative $J/\psi <p_T>$ increases with the mid-rapidity relative event multiplicity and then saturates beyond $dN_{ch}/d\eta/\langle dN_{ch}/d\eta \rangle \sim 1.5$.

The same behavior is observed for forward and backward rapidity $J/\psi$. 
ALICE has performed a measurement of $J/\psi$ production in p-Pb collisions at backward, central and forward rapidity:

- Significant suppression at mid and forward rapidity while no suppression at backward rapidity. Fair agreement with shadowing with/without coherent energy loss models.

- $R_{pPb}$ vs $p_T$ shows suppression at mid and forward rapidity for low $p_T$. Good agreement with available models, except at forward rapidity and low $p_T$.

- Simple extrapolation of CNM effects from p-Pb to Pb-Pb collisions shows a strong suppression at large $p_T$ and hints of recombination at low $p_T$.

- $Q_{pPb}$ vs event activity studied for the first time. No appreciable nuclear effects at low event activity. Suppression at forward rapidity and enhancement at backward rapidity for increasing event activity.

- Relative yields at forward and backward rapidity show a strong increase with charged particle multiplicity. Similar behavior as in pp.

- Relative $J/\psi <p_T>$ increases at low multiplicity and saturates.
THANK YOU FOR YOUR ATTENTION
\[
\frac{d^2 \sigma}{dy dp_T} = \frac{Y_{J/\psi \rightarrow \mu^+ \mu^- (e^+ e^-)}(\Delta p_T, \Delta y)}{BR(J/\psi \rightarrow \mu^+ \mu^- (e^+ e^-)) \times \Delta p_T \times \Delta y} \times \sigma_{MB}
\]

\[
Y_{J/\psi \rightarrow \mu^+ \mu^- (e^+ e^-)}(\Delta p_T, \Delta y) = \frac{N_{J/\psi \rightarrow \mu^+ \mu^- (e^+ e^-)}(\Delta p_T, \Delta y)}{N_{MB} \times A\epsilon}
\]

Cross-sections are higher in the backward rapidity region than in the forward region.

\[
\langle p_T \rangle_{0 < p_T < 15} = 2.77 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c}
\]

\[
\langle p_T \rangle_{0 < p_T < 15} = 2.47 \pm 0.01^{\text{stat.}} \pm 0.02^{\text{syst.}} \text{ GeV/c}
\]
$R_{FB}$ vs RAPIDITY

$p$-Pb $\sqrt{s_{\text{NN}}} = 5.02$ TeV, inclusive $J/\psi \rightarrow \mu^+\mu^-$, $0<p_T<15$ GeV/c

ALICE | QM2014 | 20/05/2014 | Javier Martin
### \( R_{pPb} \) UNCERTAINTIES: MIDRAPIDITY

#### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( p_T )-integrated</th>
<th>( p_T )-differential</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S. Extraction &amp; PID</strong></td>
<td>11.1 %</td>
<td>10 - 20 %</td>
</tr>
<tr>
<td>uncorr. between ( p_T ) bins</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tracking efficiency</strong></td>
<td>6 %</td>
<td>6 %</td>
</tr>
<tr>
<td>uncorr. between ( p_T ) bins</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MC kinematics</strong></td>
<td>3 %</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>( \langle T_{pPb} \rangle )</strong></td>
<td>3.4 %</td>
<td>-</td>
</tr>
<tr>
<td>fully corr. wrt. forward and backward results</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>( \sigma_{pPb}^{MB} )</strong></td>
<td>-</td>
<td>3.4 %</td>
</tr>
<tr>
<td>corr between ( p_T ) bins and wrt forward result</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>( \sigma_{pp}^{J/\psi} )</strong></td>
<td>16.6 %</td>
<td>17 - 27 %</td>
</tr>
<tr>
<td>16.6% corr. between ( p_T ) bins</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### UNCERTAINTIES: FORWARD/BACKWARD RAPIDITY

Systematic uncertainties (not exhaustive, just indicative)

<table>
<thead>
<tr>
<th></th>
<th>p-going direction</th>
<th>Pb-going direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking Efficiency</td>
<td>4 %</td>
<td>6 %</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>2.8 % (2-3.6% ****)</td>
<td>3.2 % (2-3.6% ****)</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>1.3 % (1 - 4 %)</td>
<td>1.2 % (1.2 - 6.7 %)</td>
</tr>
<tr>
<td>MC input</td>
<td>1.5 % (0.1 - 3 %)</td>
<td>1.5 % (0.1 - 4.2 %)</td>
</tr>
<tr>
<td>Matching efficiency</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>F</td>
<td>1 %</td>
<td>1 %</td>
</tr>
<tr>
<td>$\sigma_{pp/\psi}$ **</td>
<td>4.3 % (3.1 - 6.0 %)</td>
<td>4.6 % (1.5 - 13.4 %)</td>
</tr>
<tr>
<td>$&lt;T_{pPb}&gt;$ ***</td>
<td>(1.5-9.5 %)</td>
<td>(1.5-9.5 %)</td>
</tr>
<tr>
<td>$\sigma_{pPb}$ MB *</td>
<td>3.2 %</td>
<td>3 %</td>
</tr>
<tr>
<td>$\sigma_{pp/\psi}$ **</td>
<td>3.7 % (2.7 - 9.2 %)</td>
<td>3.1 % (1.2 - 8.3 %)</td>
</tr>
<tr>
<td>Pile-up ***</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>B.R</td>
<td></td>
<td>1 %</td>
</tr>
<tr>
<td>$&lt;T_{pPb}&gt;$ **</td>
<td>3.6 %</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{pp/\psi}$ **</td>
<td></td>
<td>5.5 %</td>
</tr>
</tbody>
</table>

* for $\sigma_{pPb}$/\psi only
** for $R_{pPb}$ and $Q_{pPb}$ only
*** for $Q_{pPb}$ and $\sigma_{pPb}$/\psi in ev. act bins only
**** for $p_T$ bins only

Uncorrelated (in $p_T/y$ and betw. systems)
Partially correlated (c. in $p_T/y$, uc. betw. systems)
Correlated (fully correlated)

Note: The sharing of the uncertainties may change slightly in event activity bins depending on the quantities plotted.
J/ψ signal extraction and \( <p_T> \) extraction from J/ψ Acc \( \times \varepsilon(p_T, y) \) corrected spectra in multiplicity bins

Yield extraction procedure similar to previous analysis, for \( <p_T> \) a different method used:

\[
< p_T >^{\mu^+ \mu^-} (M_{\mu^+ \mu^-}) = \alpha^{J/\psi} (M_{\mu^+ \mu^-}) \times < p_T >^{J/\psi} + \alpha^{\psi'} (M_{\mu^+ \mu^-}) \times < p_T >^{\psi'} + (1 - \alpha^{J/\psi} (M_{\mu^+ \mu^-}) - \alpha^{\psi'} (M_{\mu^+ \mu^-})) \times < p_T >^{bkg}
\]

Based on Signal-Background ratio:

\[
\alpha(M_{\mu^+ \mu^-}) = \frac{S(M_{\mu^+ \mu^-})}{S(M_{\mu^+ \mu^-}) + B(M_{\mu^+ \mu^-})}
\]

\( < p_T >^{J/\psi} \rightarrow \text{constant} \)

\( < p_T >^{\psi'} \rightarrow \text{constant} \)

\( < p_T >^{bkg} = \text{pol2} \)
### RELATIVE YIELD AND $<p_T>$ vs MID-$\gamma$

#### RELATIVE MULTIPLICITY UNCERTAINTIES

Only uncorrelated systematic uncertainties remain at first order in relative quantities

<table>
<thead>
<tr>
<th></th>
<th>Forward-(\gamma)</th>
<th>Backward-(\gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraction method (N_{J/\psi}^{\text{bin}})</td>
<td>1.5-7 %</td>
<td>1.5-7 %</td>
</tr>
<tr>
<td>S. Extraction (N_{J/\psi}^\text{bin}/N_{J/\psi})</td>
<td>1.5-3.3 %</td>
<td>1.5-4.6 %</td>
</tr>
<tr>
<td>$&lt;p_T&gt;$ MC input</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Extraction $&lt;p_T&gt;/&lt;p_T&gt;_{\text{int.}}$</td>
<td>0.1-0.4 %</td>
<td>0.1-1.2 %</td>
</tr>
<tr>
<td>F</td>
<td>1-7 %</td>
<td>1-4%</td>
</tr>
<tr>
<td>$&lt;dN_{\text{ch}}/d\eta&gt;$</td>
<td>3.9%</td>
<td>3.9%</td>
</tr>
<tr>
<td>Pile up</td>
<td>1-4%</td>
<td>1-2%</td>
</tr>
</tbody>
</table>
$p_T$-DIFFERENTIAL CROSS SECTION

EVENT ACTIVITY DEPENDENCE

Inclusive $J/\psi \rightarrow \mu^+\mu^-$, p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

-4.46<$y_{\text{cms}}<$-2.96, Pb-going direction

ALICE Preliminary

Glob.syst. 3.2%

ZN Energy Event Classes:
- 5-10% (x20)
- 10-20% (x10)
- 20-40% (x5)
- 40-60% (x5)
- 60-80% (x5)
- 80-100% (x5)

Inclusive $J/\psi \rightarrow \mu^+\mu^-$, p-Pb $\sqrt{s_{NN}} = 5.02$ TeV

2.03<$y_{\text{cms}}<$3.53, p-going direction

ALICE Preliminary

Glob.syst. 3.4%

ZN Energy Event Classes:
- 5-10% (x20)
- 10-20% (x10)
- 20-40% (x5)
- 40-60% (x5)
- 60-80% (x5)
- 80-100% (x5)
\textbf{Q}_{\text{pPb}} \text{ vs } p_T : \text{ EVENT ACTIVITY DEPENDENCE}

\begin{itemize}
  \item \textbf{Increase} of $Q_{\text{pPb}}$ for increasing event activity at \textbf{backward} rapidity. A $p_T$ dependence is also observed, showing a stronger enhancement at high $p_T$.
  \item \textbf{Decrease} of $Q_{\text{pPb}}$ for increasing event activity at \textbf{forward} rapidity. A $p_T$ dependence is also observed, showing stronger suppression at low $p_T$.
\end{itemize}
• For increasing event activity the difference between forward and backward rapidity results becomes much stronger
$<p_T>$ vs EVENT ACTIVITY

- $<p_T>$ shows an increase with the event activity at forward and backward rapidity.
- $<p_T>$ is systematically higher at forward than at backward rapidity.
• $\Delta <p_T^2>_{J/\psi}$ compatible with pp value for the lowest energy event class

• $\Delta <p_T^2>_{J/\psi}$ increases with energy event class

• $\Delta <p_T^2>_{J/\psi}$ values systematically higher at forward than at backward rapidity
p-Pb $\sqrt{s_{NN}}= 5.02$ TeV, inclusive $J/\psi \rightarrow \mu^+ \mu^-$


• Results in good agreement within uncertainties
• Results in good agreement within uncertainties

\[ \text{p-Pb } \sqrt{s_{NN}} = 5.02 \text{ TeV, inclusive } J/\psi \rightarrow \mu^+\mu^- \]

\[ R_{FB} \]

\[ \begin{array}{c}
\hline
p_T (\text{GeV/c}) \\
\hline
0 & 2 & 4 & 6 & 8 & 10 & 12 & 14 \\
\hline
\end{array} \]

\[ y_{\text{cms}} \]

\[ 2.4 \leq y_{\text{cms}} \leq 4 \]

• Results in good agreement within uncertainties
\[ p\text{-}Pb \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{ inclusive } J/\psi \rightarrow \mu^+\mu^- \]

- Results in good agreement within uncertainties